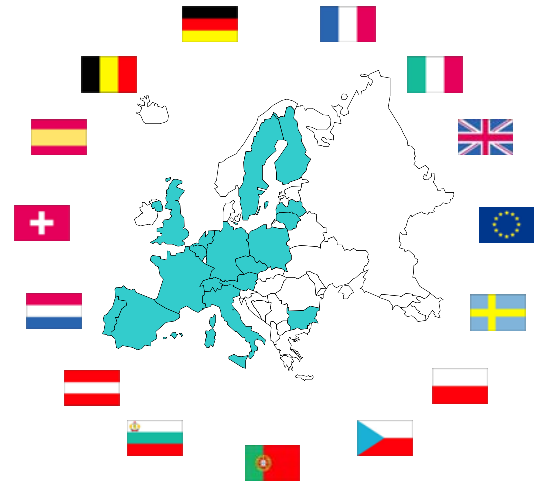


Accelerator R&D

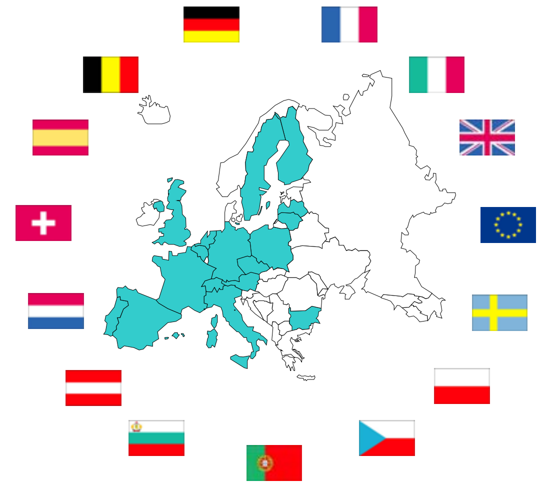
for the

European ADS demonstrator

J-Luc BIARROTTE, CNRS-IN2P3 / IPN Orsay, France

On behalf of the EUROTRANS WP1.3 working group

IPN Orsay Division Accélérateur
CNRS dépasser les frontières
In2p3



1. The European ADS demonstrator project

2. The XT-ADS linac reference scheme

3. The reliability issue

4. Related R&D topics

5. Conclusion

1. **Overall purpose**

    - Reduce the nuclear wastes radio-toxicity, volume & heat load before underground storage

    - 2500 tons of spent fuel are produced every year by the EU reactors (25 t Pu, 3.5 t MA, 3 t LLFP)

2. **Available strategy: P&T**

    - **P**artitioning: chemical separation of Pu, MA & FP

    - **T**ransmutation: use of the waste as a fuel in DEDICATED transmuter systems

3. **The ADS transmuter system**

    - A subcritical reactor (k_{eff}<1), in which the chain reaction is not self-sustained

    - An intense spallation source, that provides the "missing" neutrons

From ETWG Report, 2001

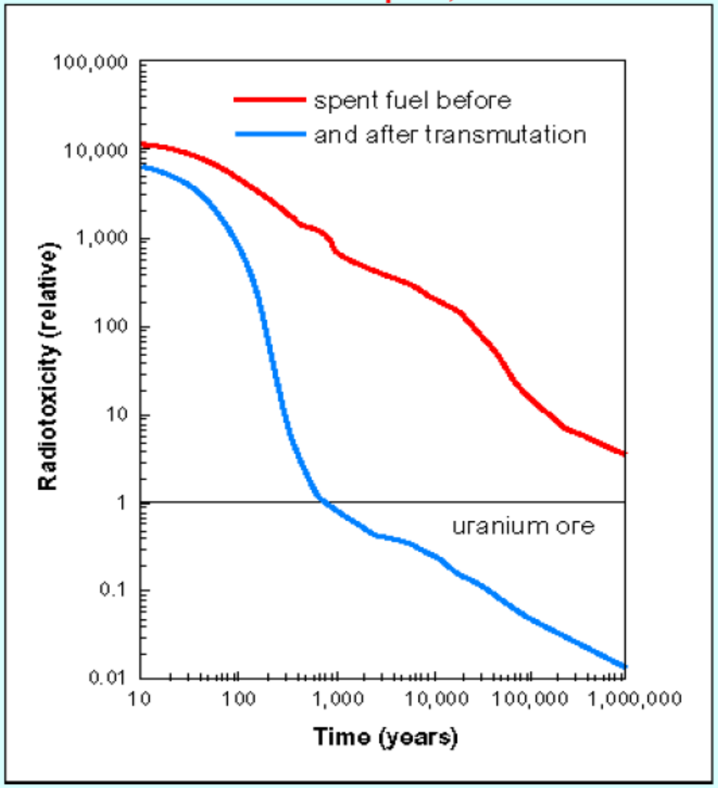


Fig. 1 – Ingestion radio-toxicity of 1 ton of spent nuclear fuel. With a separation efficiency of 99.9% of the long-lived by-products from the waste, followed by transmutation, reference radio-toxicity levels can be reached within 700 years

The EUROTRANS programme

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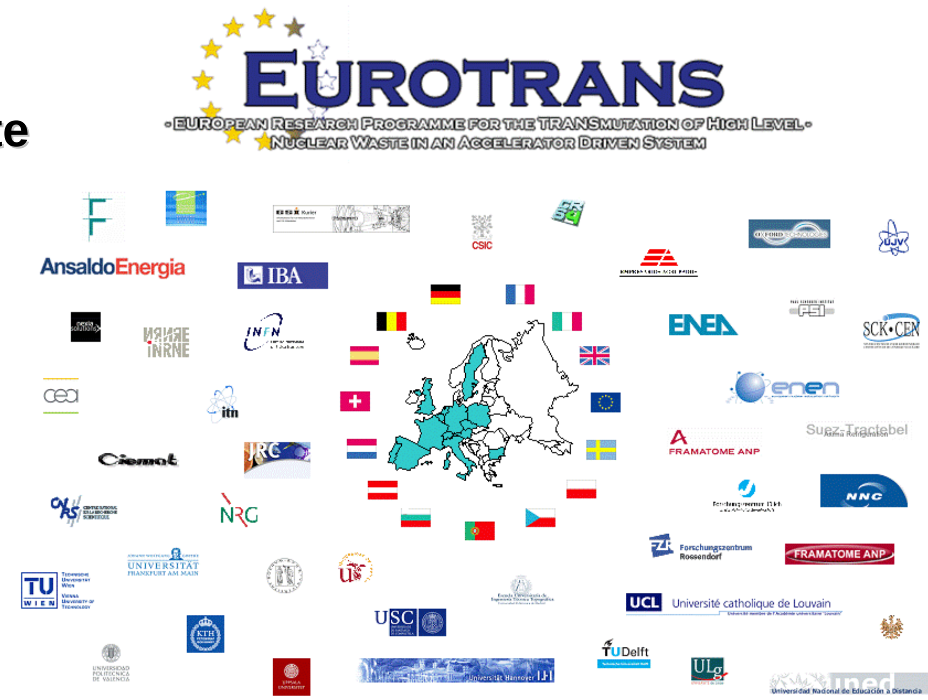
SIXTH FRAMEWORK PROGRAMME

- **EURopean research programme for the TRANSmutation of high level nuclear waste in an Accelerator Driven System**
- EU FP6 programme (2005-2010)
- More than 40 research agencies, universities & nuclear industries
- Expands the EU FP5 project PDS-XADS (2001-2004)
- Includes 5 distinct research Domains (**see also J-M.DE CONTO TU6PFP028**)



Main GOAL of the EUROTRANS programme

- Advanced design of a 50-100 MWth eXperimental facility demonstrating the technical feasibility of Transmutation in an ADS **(XT-ADS/MYRRHA, short-term realisation)**
- Generic conceptual design (several 100 MWth) of a European Facility for Industrial Transmutation **(EFIT, long-term realisation)**

Transmutation Demonstration

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1. MYRRHA/XT-ADS (ADS prototype)

- Goals:
  - **Demonstrate the concept** (coupling of accelerator + spallation target + reactor),
  - **Demonstrate the transmutation**
  - **Provide a fast-spectrum irradiation facility** for material & fuel developments

- Features:
  - 50-100 MWth power
  - k_{eff} around 0.95
  - 600 MeV, 2.5 mA proton beam
  - Highly-enriched MOX fuel
  - Pb-Bi Eutectic coolant & target

2. EFIT (Industrial Transmuter)

- Goals:
  - Maximise the transmutation efficiency
  - Easiness of operation and maintenance
  - High level of availability for a cost-effective transmutation

- Features:
  - Several 100 MWth power
  - k_{eff} around 0.97
  - 800 MeV, 20 mA proton beam
  - Minor Actinide fuel
  - Pb coolant & target (gas as back-up solution)

Proton beam specifications

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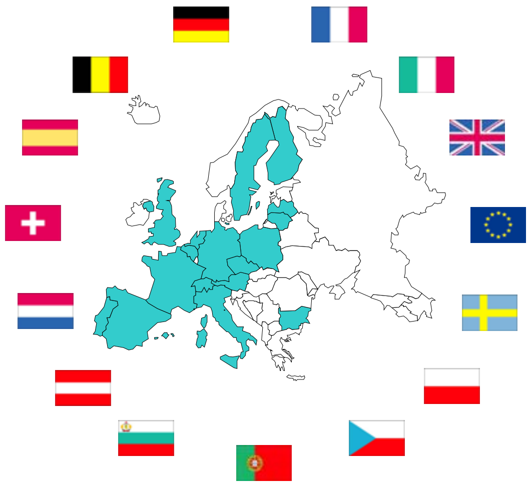
High-power proton CW beams

Table 1 – XT-ADS and EFIT proton beam general specifications

	XT-ADS	EFIT
Maximum beam intensity	2.5 – 4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertically from above	
Beam trip number	< 20 per year (exceeding 1 second)	< 3 per year (exceeding 1 second)
Beam stability	Energy: ± 1 %, Intensity: ± 2 %, Size: ± 10 %	
Beam footprint on target	Circular ∅ 5 to 10 cm, "donut-shaped"	An area of up to 100 cm² must be "paint-able" with any arbitrary selectable intensity profile
Beam time structure	CW, with 200 µs zero-current holes every 10^{-3} to 1 Hz, + pulsed mode capability (repetition rate around 50 Hz)	

Extrememely high reliability required !!!



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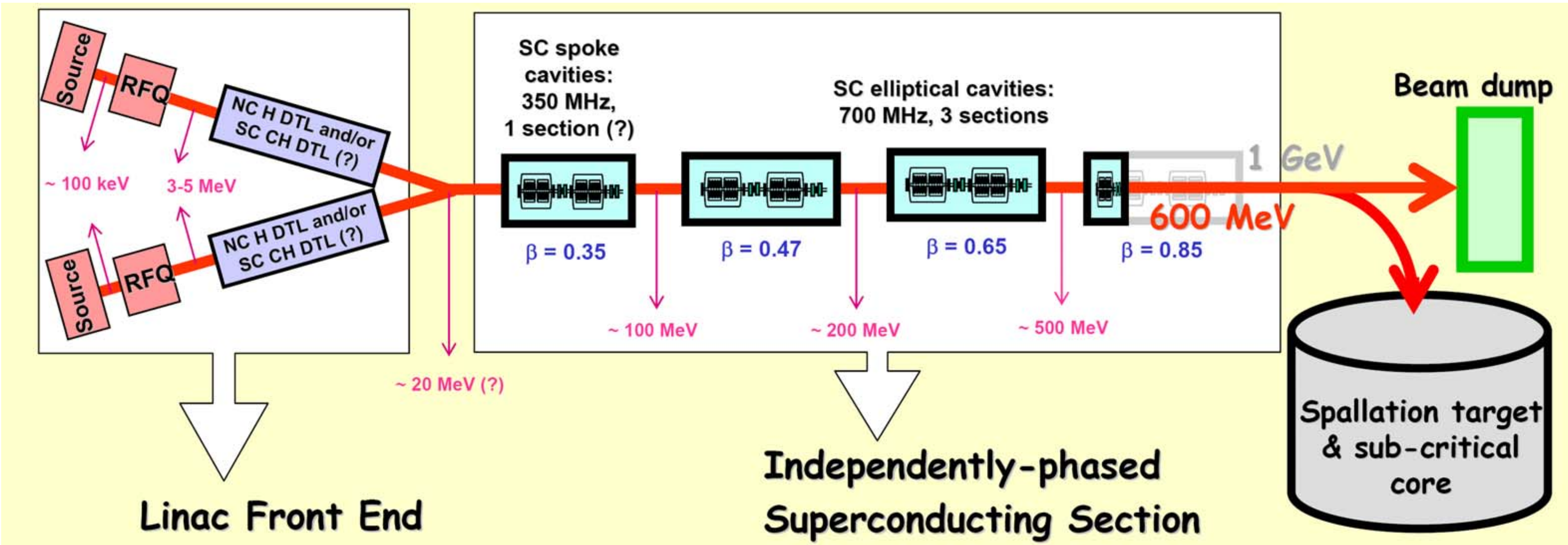
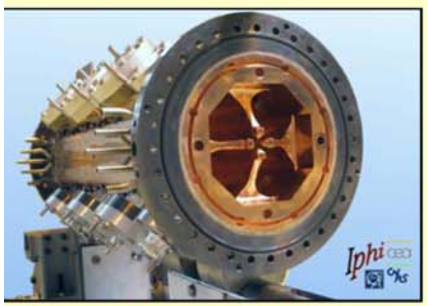
ADS linac reference scheme

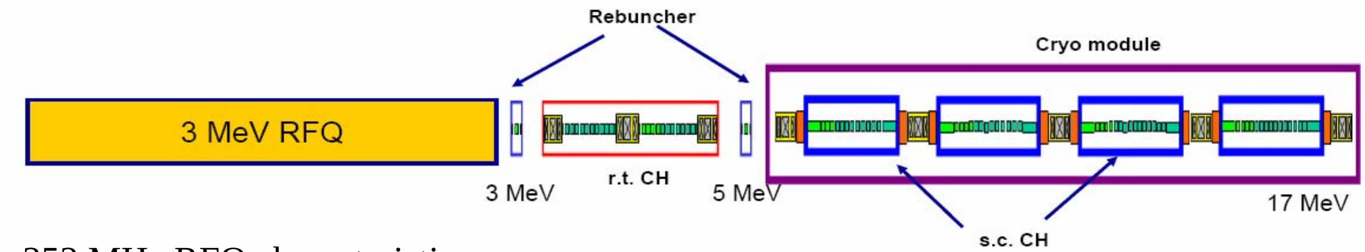
SUPERCONDUCTING LINAC

Highly modular and upgradeable; Excellent potential for reliability ; Very good efficiency





Linac front-end



Johann Wolfgang Goethe Universität Frankfurt am Main

352 MHz RFQ characteristics

Parameters	Values
Beam Current [mA]	30
Frequency [MHz]	352
Input Energy [keV]	50
Output Energy [MeV]	3.0
Inter-Electrode Voltage [kV]	65
Kilpatrick Factor	1.69
$\varepsilon_{in}^{trans., n., rms}$ [π mm-mrad]	0.20
Output Synchronous Phase [°]	-28.8
Minimum Aperture [cm]	0.23
Maximum Modulation	1.79
$\varepsilon_{out}^{x., n., rms}$ [π mm-mrad]	0.21
$\varepsilon_{out}^{y., n., rms}$ [π mm-mrad]	0.20
$\varepsilon_{out}^{z, rms}$ [MeV-deg]	0.09
Electrode Length [cm]	431.8
Beam Transmission [%]	99.9

IN-WORK

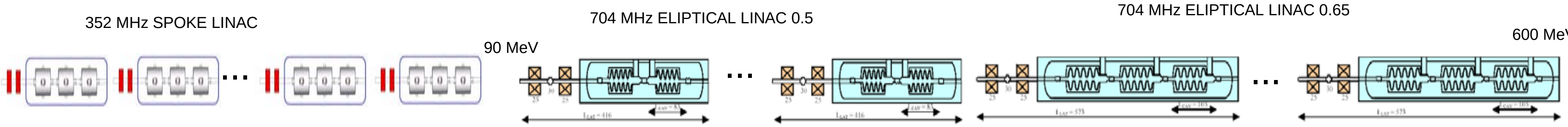
352 MHz DTL characteristics

Cavity	Gaps (φ_s [°])	Length [cm]	$W_{s,out}$ [MeV]	Eacc* [MV/m]
Rebuncher I	2 (-90°)	~7	3.0	2.79
RT-CH	11 (0°) 4 (-40°) 8 (0°)	~160	5.2	2.72
Rebuncher II	2 (-90°)	~7	5.2	5.11
SC-CH I	3 (-40°) 10 (0°)	~90	7.5	3.99
SC-CH II	4 (-40°) 10 (0°)	~105	10.4	3.97
SC-CH III	4 (-40°) 12 (0°)	~130	14.3	3.98
SC-CH IV	4 (-40°) 12 (0°)	~145	18.3	3.96

* Eacc: active acceleration gradient.

- Classical 4-vane RFQ with moderated Kp
- DTL booster using CH structures (KONUS beam dyn.)
- 17 MeV gained in less than 15 metres

Superconducting linac



Section number	1	2	3	4
Input Energy [MeV]	17	90	190	450
Output Energy [MeV]	90	190	450	610
Cavity Technology	Spoke 352 MHz	Elliptical 704 MHz		
Structure β	0.35	0.47	0.65	0.85
Number of cavity cells	2	5	5	6
Number of cavities	60	30	42	16
Focusing type	NC quadrupole doublet			
Cavities/Lattice	3	2	3	4
Synch Phase [deg]	-40 to -18	-36 to -15		
Lattice length [m]	2.5	4.1	5.7	8.4
Section Length [m]	50	61	80	34
<gradient> [MeV/m]	1.4	1.6	3.4	4.7

IN-WORK

- Modular, independently-phased accelerating structures
- Moderate gradients (50mT B_{pk}, 25MV/m E_{pk}) & energy gain per cavity
- Overall length: about 225 metres

Final beam line to reactor

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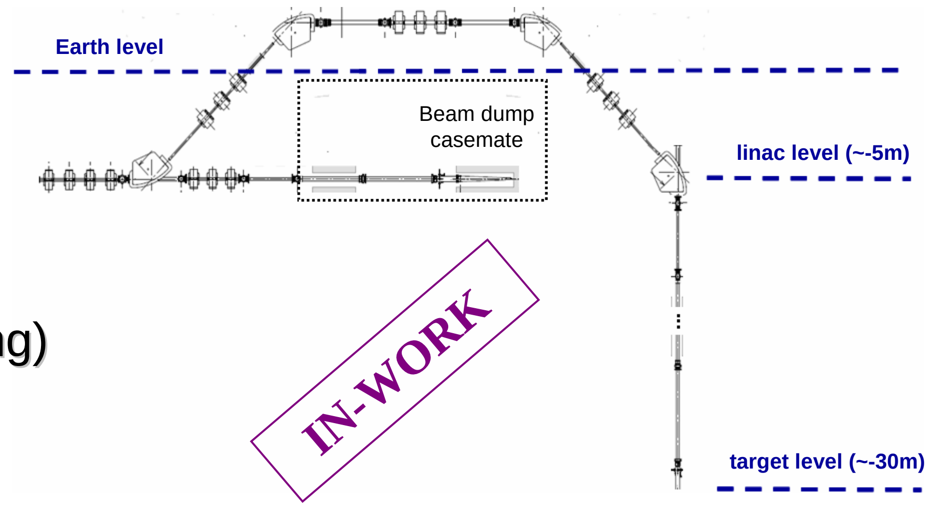
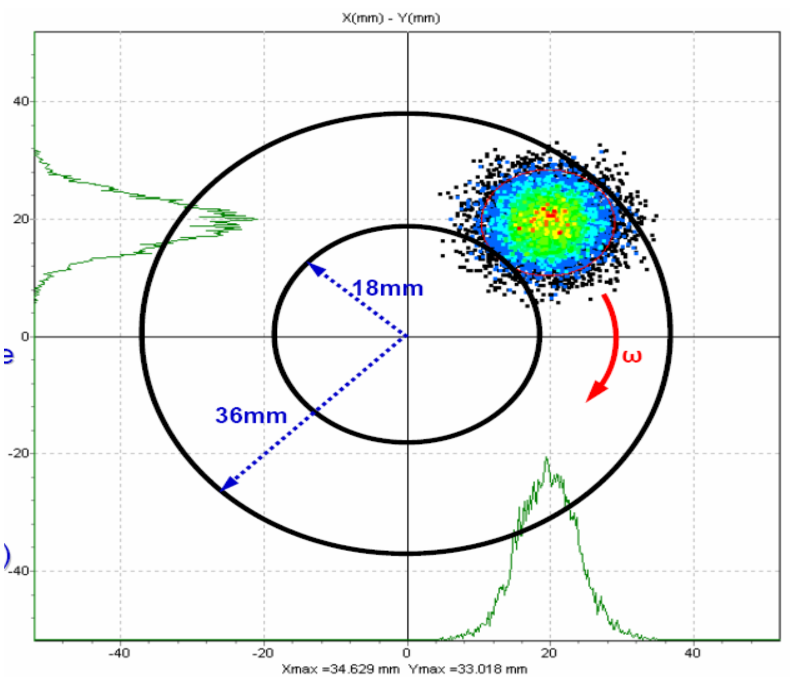
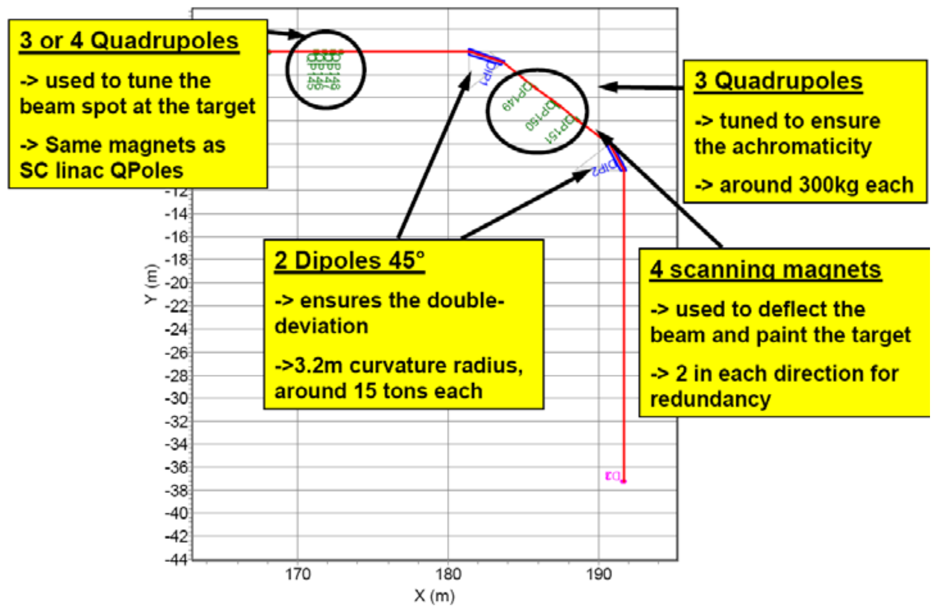
- Final beam line guarantees the position of the beam spot and ensures that only particles of nominal energy are delivered (doubly-achromatic lines)

- Also guarantees the required “donut-shape” distribution at the target (redundant beam scanning)







Beam dynamics

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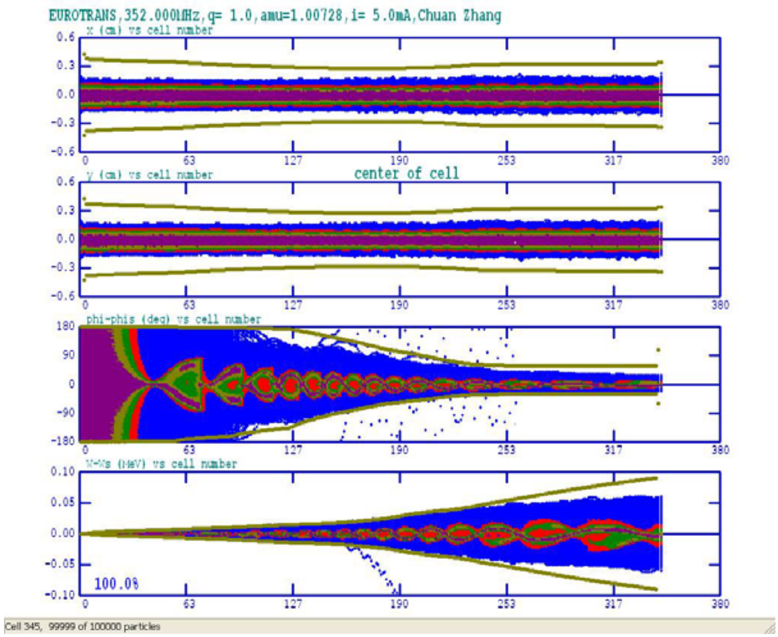
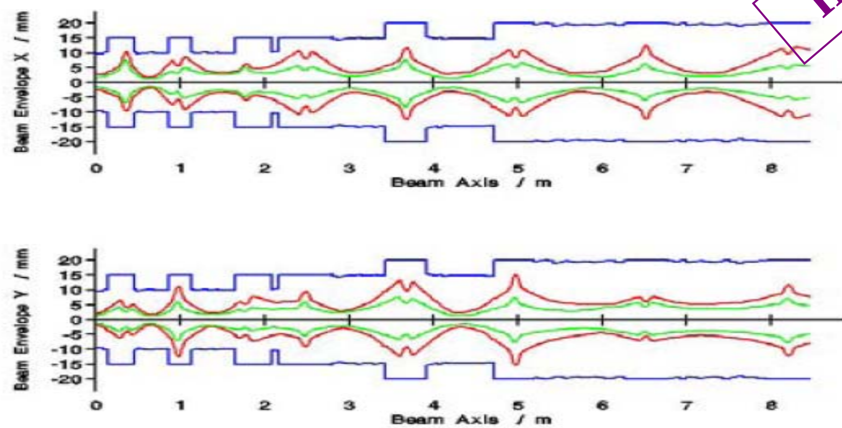
IN-WORK

Less than 10% emittance growth in the whole 17 MeV front-end

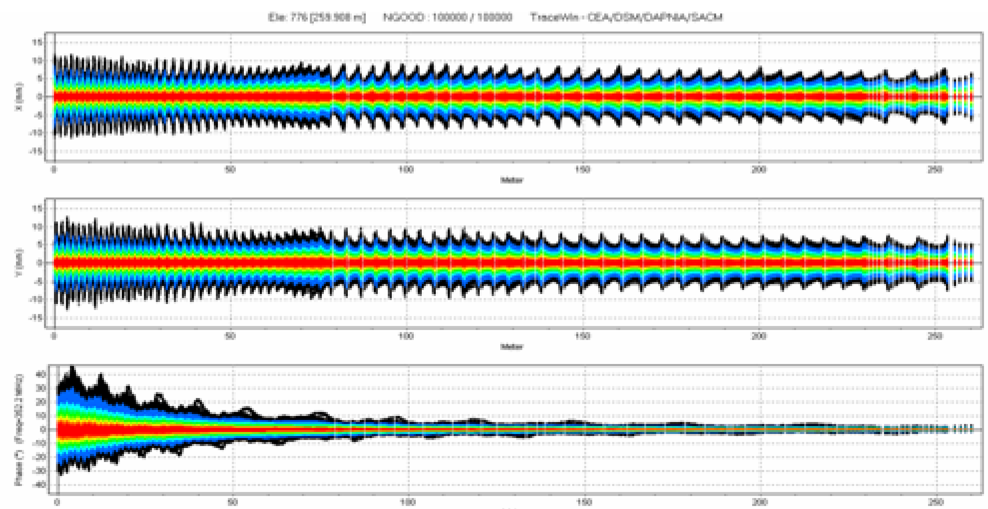
(RFQ simulations with PARMTEQM, DTL simulations with LORASR)





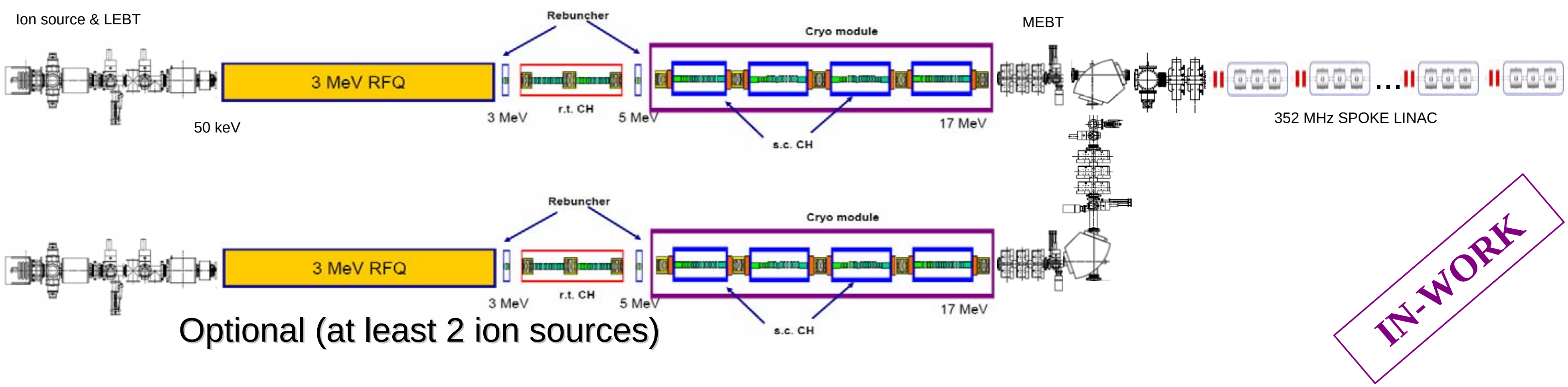
Less than 5% emittance growth in the 17-600 MeV SC linac section

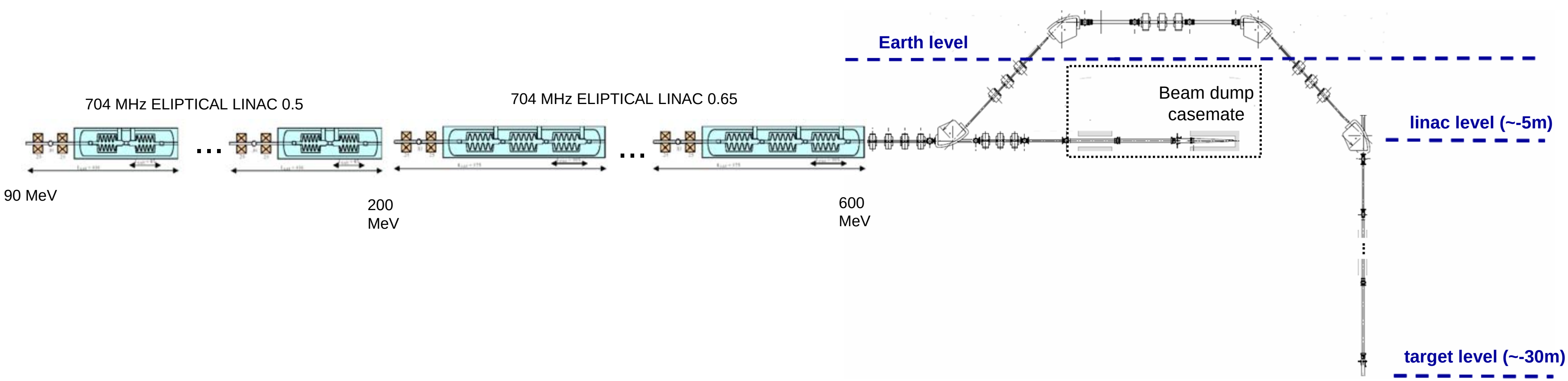
(simulations with TRACEWIN)



Advanced reference design

Goal = reach a frozen advanced design by 2010...





Advanced reference design

... with assessed start-to-end beam dynamics

TraceWin (CEA)

- ✓ Envelope code with 1st order space charge
- ✓ Interacting with GenLinWin for the SC linac longitudinal optimization

Benchmarked with: Transport (CERN), Beta (CEA), Path (CERN)…

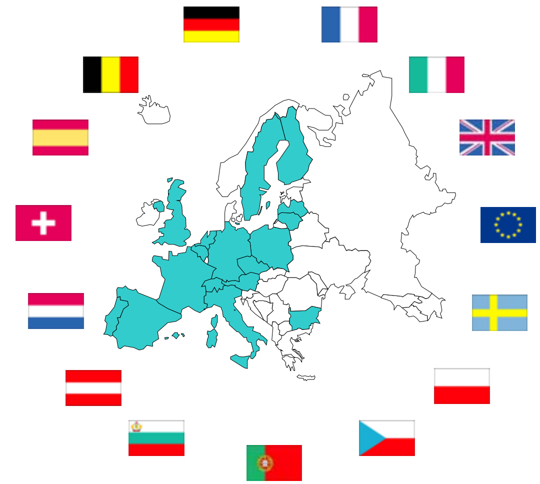
Partran (CEA)

- ✓ Multiparticle code, with 3D space charge routines.
- ✓ Coupling with TOUTATIS (CEA) for RFQ multiparticle simulations

Benchmarked with: Lions (GANIL), Impact (LANL), Dynamion (GSI), Parmila (LANL), Alodyn (INFN), Path (CERN)…

Code package crucial capabilities

- ✓ « Close to real » beam tuning procedures using simulated diagnostics
- ✓ Use of 3D field maps for most of the elements (focusing magnets, RF cavities), high-order aberrations taken into account for the others (dipoles)
- ✓ Possibility to perform statistical error studies



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The reliability requirement

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- **Beam trips longer than 1 sec are forbidden** to avoid thermal stresses & fatigue on the ADS target, fuel & assembly & to provide good availability.
  SPECIFICATION : less than 5 per 3-month operation cycle (MYRRHA / XT-ADS)

- **Reliability guidelines have been followed during the ADS accelerator design**

1. Strong component design ("**overdesign**")
   - All components are derated with respect to technological limitations
   - For every linac main component, a prototype is being designed, built and tested
2. Inclusion of **redundancies** in critical areas
   - Possible doubled front-end (hot stand-by injector), solid-state RF power amplifiers where possible…
3. Enhance the capability of **fault-tolerant** operation
   - "Fault-tolerance" = ability to pursue operation despite some major faults in the system
   - Expected in the independently-phased superconducting linac
     (for both RF faults and QP doublets faults)

Local compensation method

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CONTEXT: We have a strongly non-relativistic beam, and any energy loss will imply a phase slip along the linac, increasing with the distance, that will push the beam out of the stability region -> BEAM LOSS

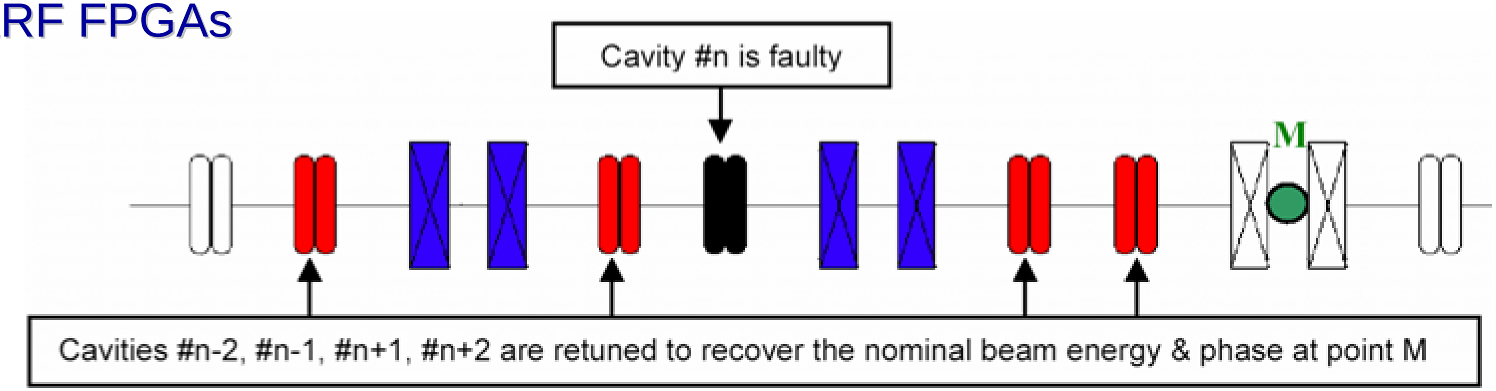
GOAL: Recover most of the SCRF cavities fault conditions without stopping/loosing the beam more than 1sec

STRATEGY:

- "Local compensation method" in the case of a RF unit or cavity failure : adjacent cavities are retuned to provide the missing energy gain to the beam

- Requires independently-powered RF cavities, good velocity acceptance, moderate energy gain per cavity & tolerant beam dynamics design

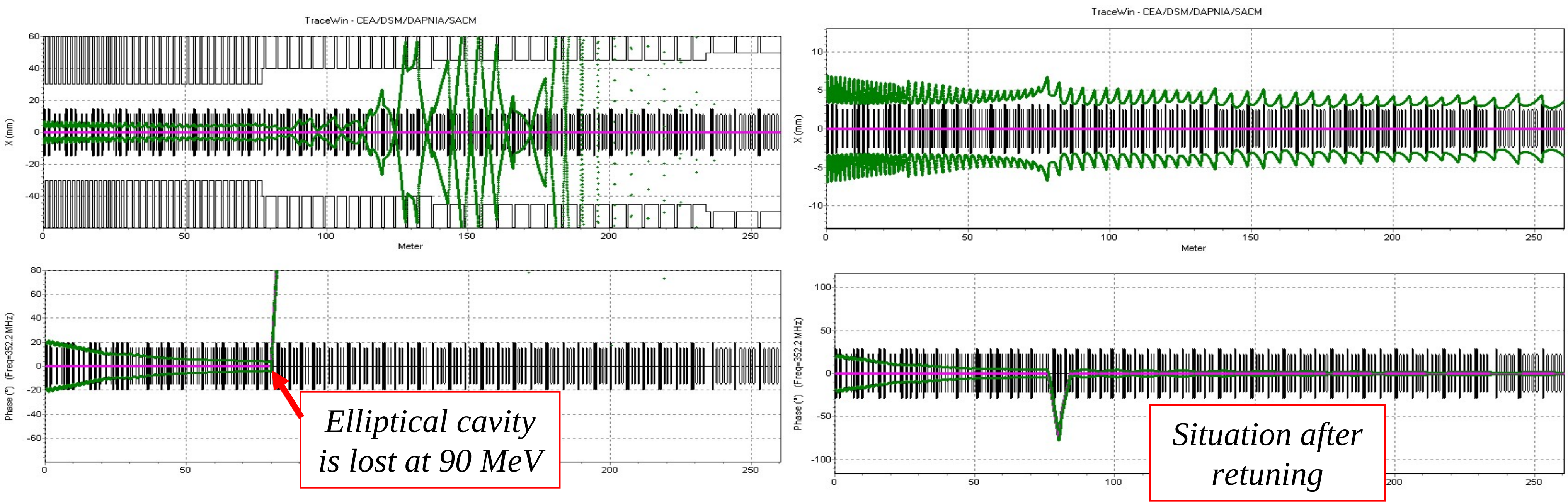
- FAST retuning to be performed using pre-tabulated set-points databases stored into the digital LLRF FPGAs



Tolerance to RF faults

In every case, with an appropriate retuning, the beam can be transported up to the high-energy end without any beam loss (100 % transmission, small emittance growth), and within the nominal target parameters.

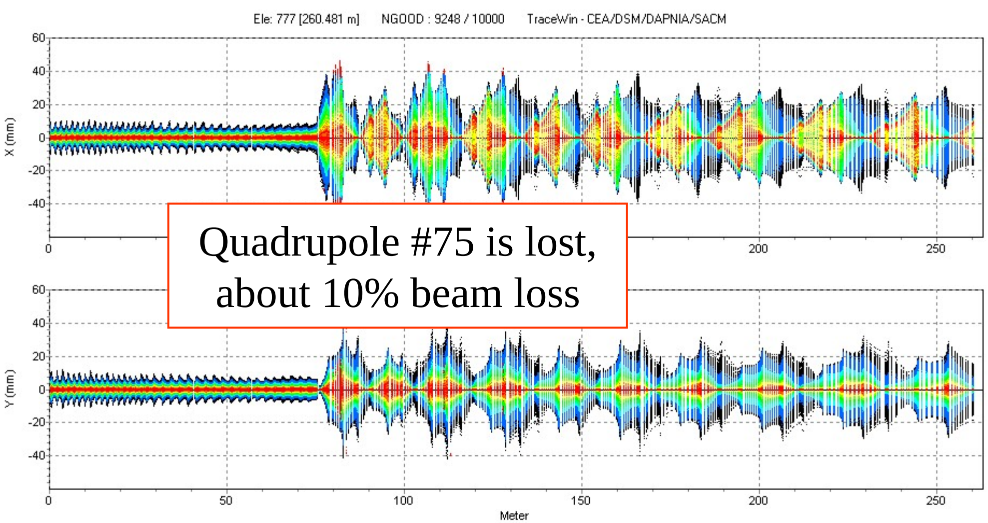
- from 4 to 8 surrounding cavities are used
- 20 to 30% margin on RF powers and accelerating fields is required
- OK for all energies from 5 to 600 MeV, but significantly more difficult below 15 MeV

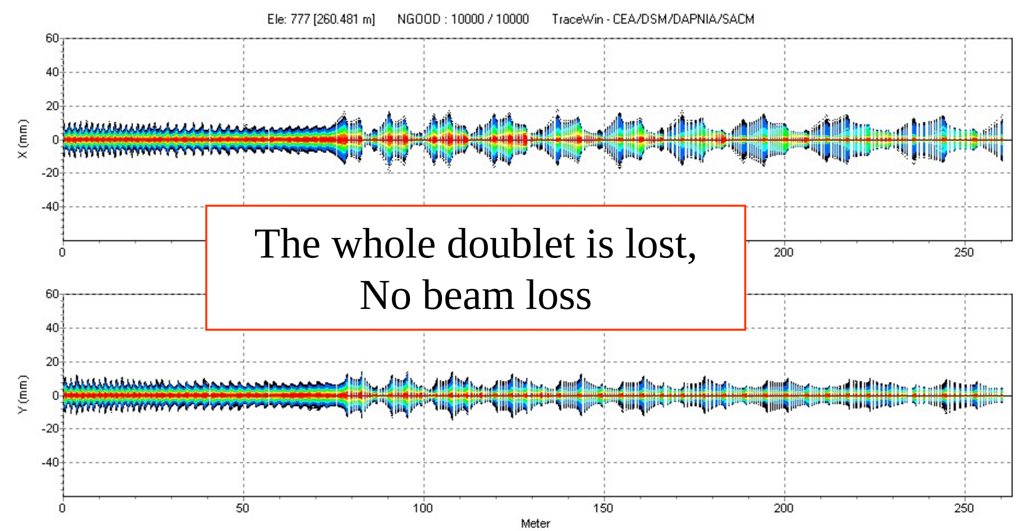


Tolerance to focusing faults

Same phylosophy can be applied to quadrupole failures

- The situation is less critical : if a quadrupole fails, beam losses occur, BUT if the whole doublet fails, no loss: it is thus recommended to <u>have 1 power supply per doublet</u>





- After a QP doublet failure, a (slow) additional retuning of neighboring doublets is recommended to decrease mismatching

Fast fault-recovery scenario

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SIXTH FRAMEWORK PROGRAMME

OK... but retuning should be performed in less than 1 second in the case of a failure event

➲ **Simulation code development**

- Based on TraceWin (CEA)

- For all the linac cavities, a RF cavity model w/ control loop is included

- Very powerful tool, able to analyze the effect of time-dependent perturbations while simulating the whole beam behavior (long. + transv. planes)

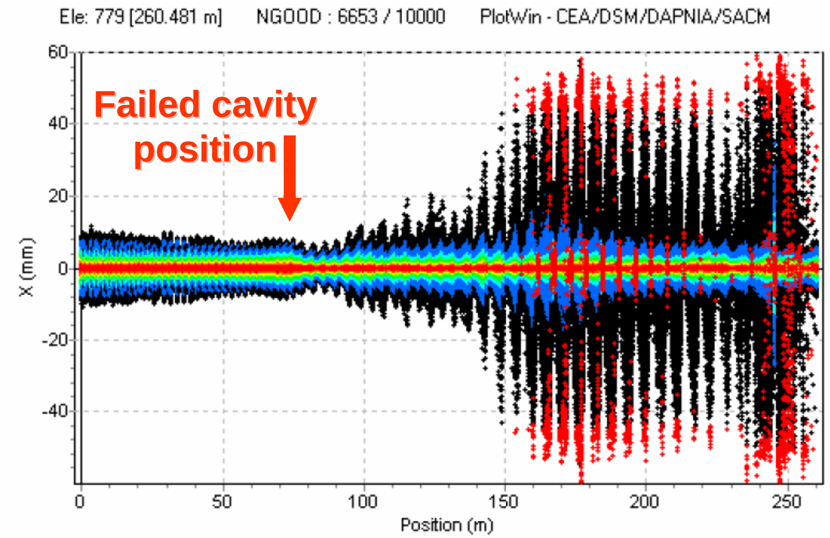


Figure 12 : Transverse beam distribution at 220 µs, in red are plotted the losses

➲ **Definition of a reference "fast fault-recovery scenario"**

< 1 sec

- **detect (or anticipate) the RF fault** (via dedicated diagnostics & interlocks) & trigger beam shut-down

- **update the new LLRF field and phase set-points** of the correcting cavities (data have been determined & stored in FPGAs during commissioning)

- **detune the failed cavity** (w/ piezo-actuators) and cut off the failed RF loop

- **trigger beam re-injection** once steady state is reached

Linac reliability analysis

GOAL of the ANALYSIS

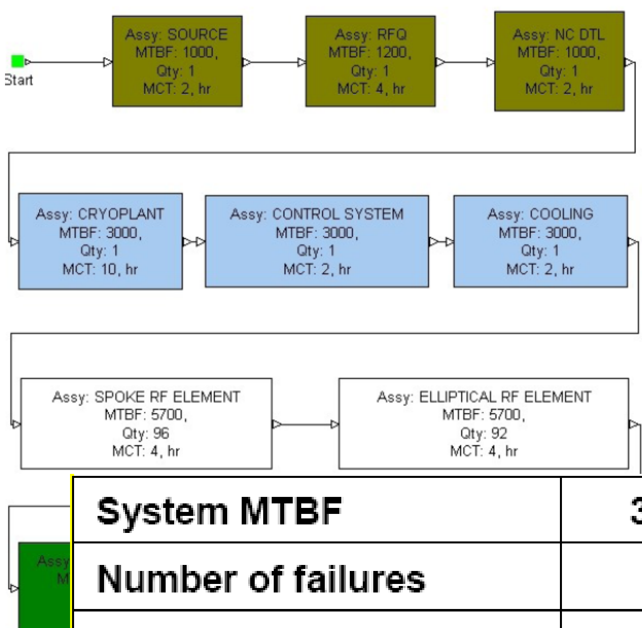
- Estimate the number of malfunctions of the XT-ADS accelerator that cause a beam/plant shutdown, per period of operation (3 months = 2190 hours)
- Analyse the influence of MTBFs (Mean Time Between Failures), MTTRs (Mean Time to Repair), and of the degree of redundancy & fault-tolerance on the results
- Goal MTBF: better than 500 hours

WORK PERFORMED SO FAR (to be continued)

- Reliability Block Diagram analysis using the Relex© software
  - performed by INFN & ENEA (PDS-XADS, 2004)
- Home-made Monte-Carlo simulations using Matlab
  - performed by Empresarios Agrupados (EUROTRANS, 2008)

CLASSICAL LINAC DESIGN

- "all-series" (simplified) components
- every component failure leads to a global system failure
- poor MTBF, mostly due to the ~150 RF units

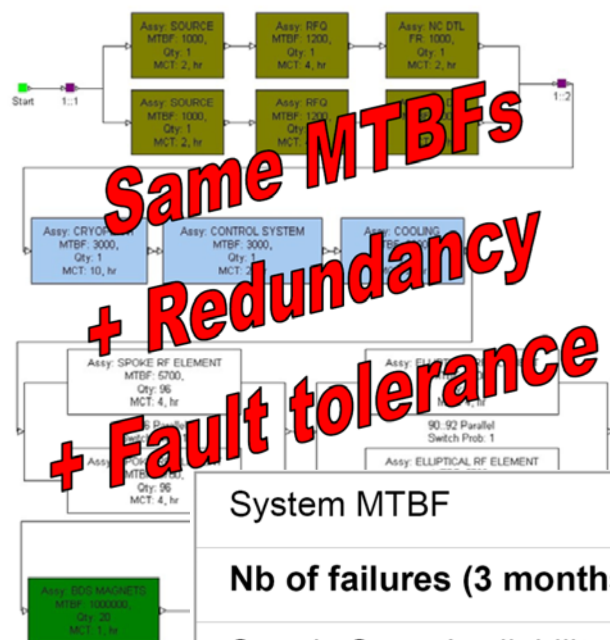


System MTBF	**31.19 hours**
Number of failures	**70.23**
Steady State Availability	**86.6 %**

RELIABILITY-ORIENTED DESIGN

- same components MTBFs
- duplicated injector with fast switching magnet
- fault-tolerance in the SC linac

If a RF accel. unit (or QP doublet) fails, a certain number of RF units are immediately retuned around the failed cavity (these sources can not be used to compensate another failure); the failed RF unit is then fixed after 1 MTTR



System MTBF	757.84 hours
Nb of failures (3 months)	**2.89**
Steady State Availability	99.5 %

★ What we learned from our RELIABILITY ANALYSIS

➲ # expected beam shutdowns from simulations

- Classical linac : ~100 per 3 months mission time
- Including fault-tolerance in the SCRF linac : ~15 per 3 months mission time
- Also including injector redundancy: ~ 5 per 3 months mission time

➲ "analysis of the analysis"

- The obtained *absolute* figures remain highly questionable (very few reliable MTBF data, high complexity of the system not fully modeled)
- Fault-tolerance & redundancy can really improve the situation, by about one order of magnitude (but of course, @ a certain cost)

★ What we learn looking @ other high power facilities

➲ Very poor reliability is generally observed

- Tens of beam trips / day

- Machines are not really designed for this issue, SNS is still young (room for improvement)

- Critical areas are usually: RF & High Voltage, ion sources & injectors, support systems (water cooling, mains), C&C and interlocks

- High-current pulsed machines are considered as less reliable than CW ones

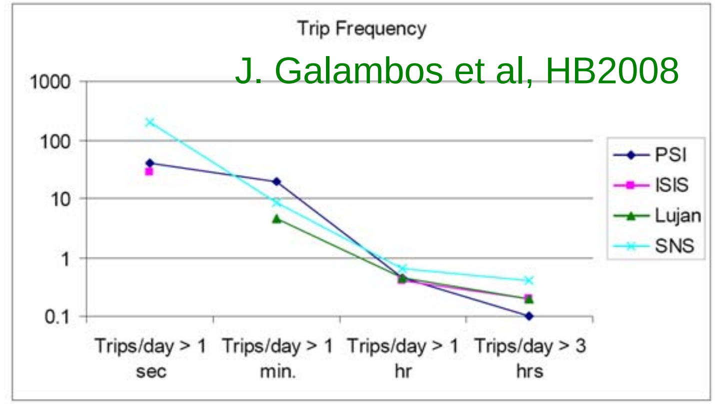
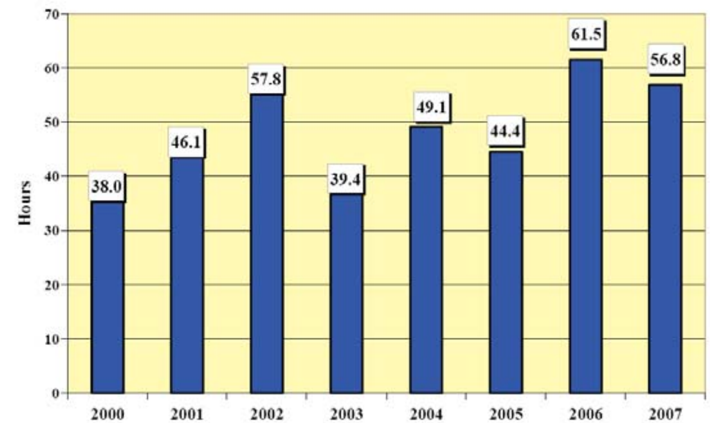


Figure 6. Trip frequency vs. trip duration for high power proton accelerators.

➲ Nevertheless, some facilities reach very interesting performance

- Very promising recent improvements at J-PARC

- Light sources facilities are more focused on reliability: ESRF (Grenoble, France) obtains routinely a MTBF of several days, and is still in progress



L. Hardy, EPAC2008

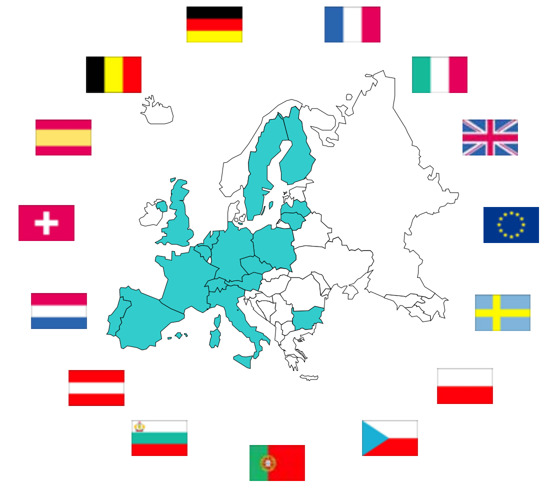
Figure 1: Evolution of the Mean Time Between Failures.

★ It seems at least not completely unrealistic to approach (and ultimately reach) the ADS accelerator reliability goal. It will imply:

- ➲ to include design de-rating, redundancy & fault-tolerance in the system
- ➲ to have a few years of commissioning and training to identify and fix the weak elements

★ Approaching the goal "from the other side" would also help !

- ➲ relaxed specifications on beam trips number
- ➲ relaxed specifications on beam trips duration
- ➲ appropriate design modifications in the target/reactor system



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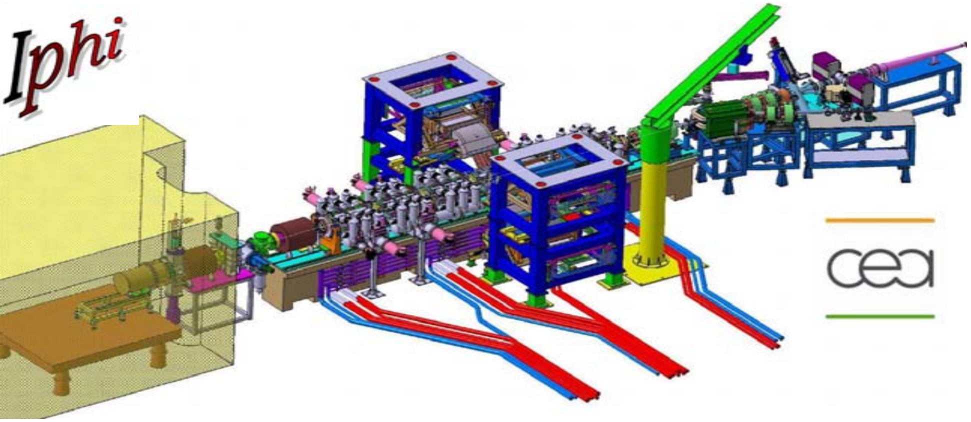
Injector long reliability test run



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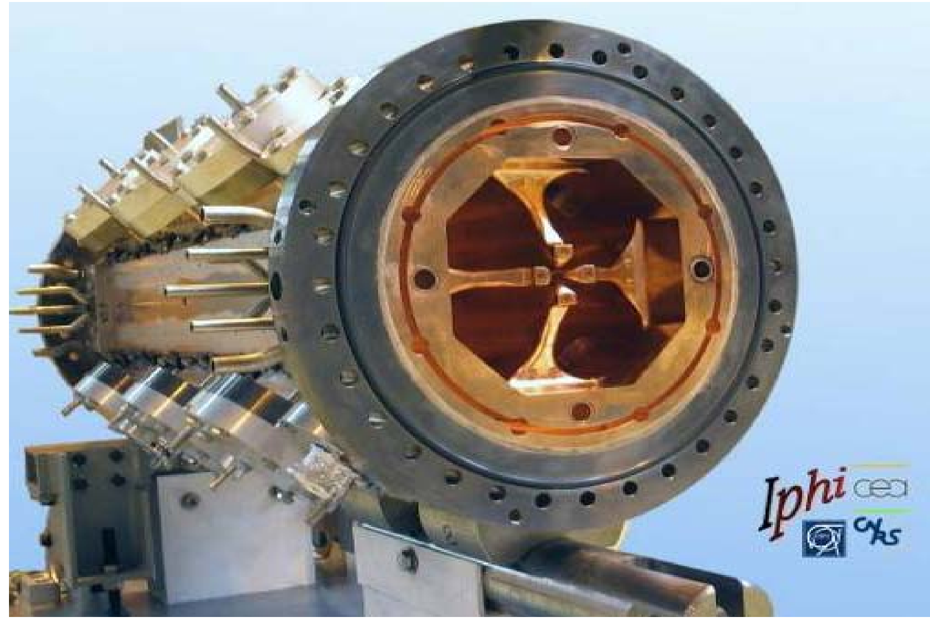


IPHI status

- SILHI ECR p source (95kV, 100mA) operational with very promising reliability

- RFQ last sections still under fabrication

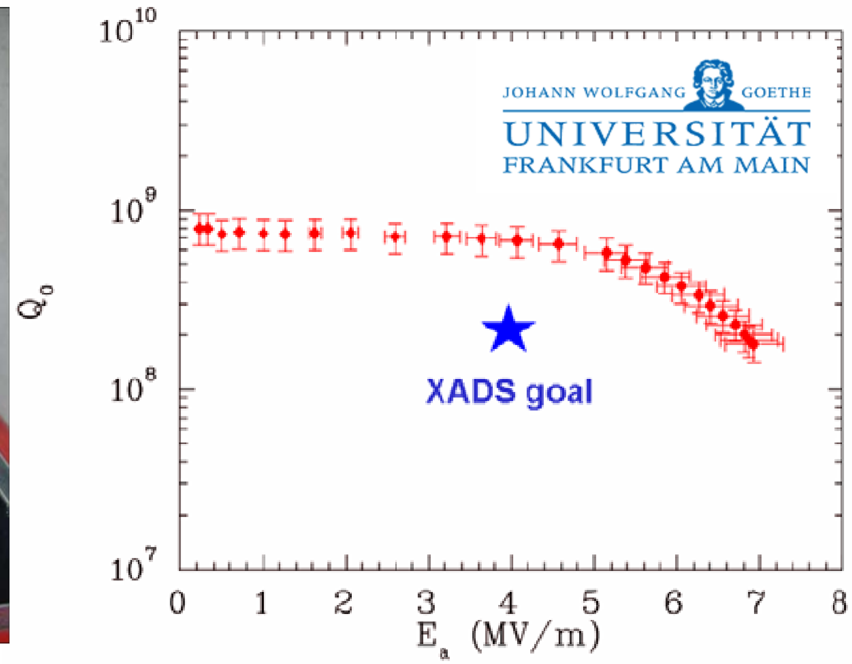
- RFQ environment 95% completed

EUROTRANS related activities

- Once IPHI commissioned, the 3 MeV beam will be continuously operated for a 2 months period @30mA

- Sharp 200μs “beam holes” have been produced successfully pulsing the source

SC CH cavities development

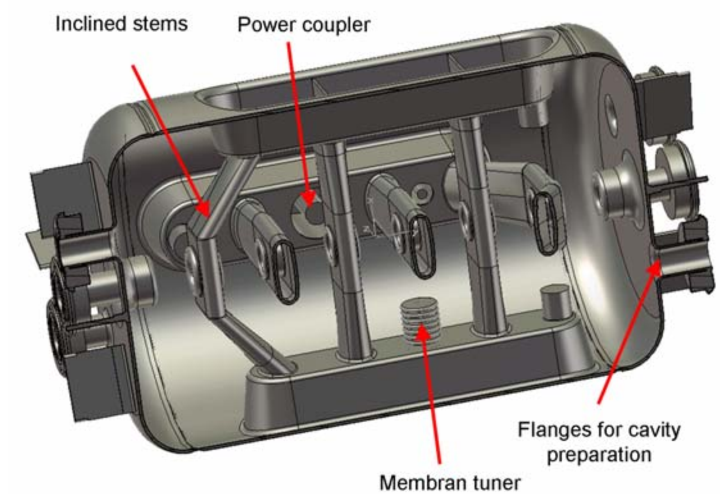


- 19-gap superconducting CH-DTL prototype built & successfully tested @4K (up to 7MV/m)

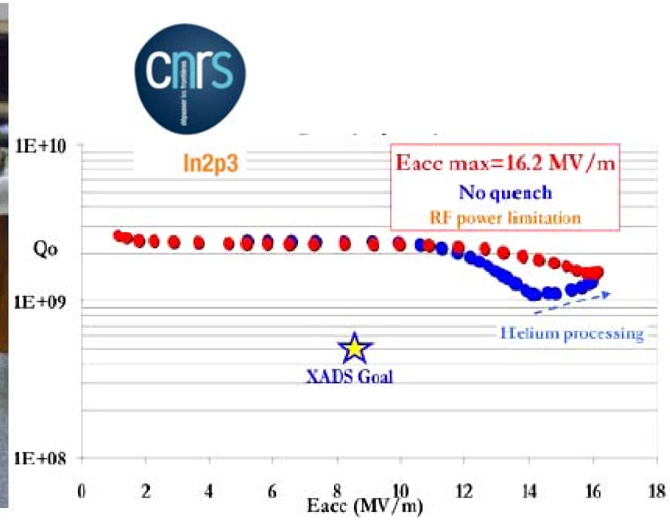
M.Busch FR5REP061

- New tests in horizontal cryostat with slow & fast tuners will come shortly

- Design of a new optimized prototype cavity suited to the XT-ADS needs (β profile, RF power needs). Construction has begun & beam tests are foreseen.



Spoke cavities development



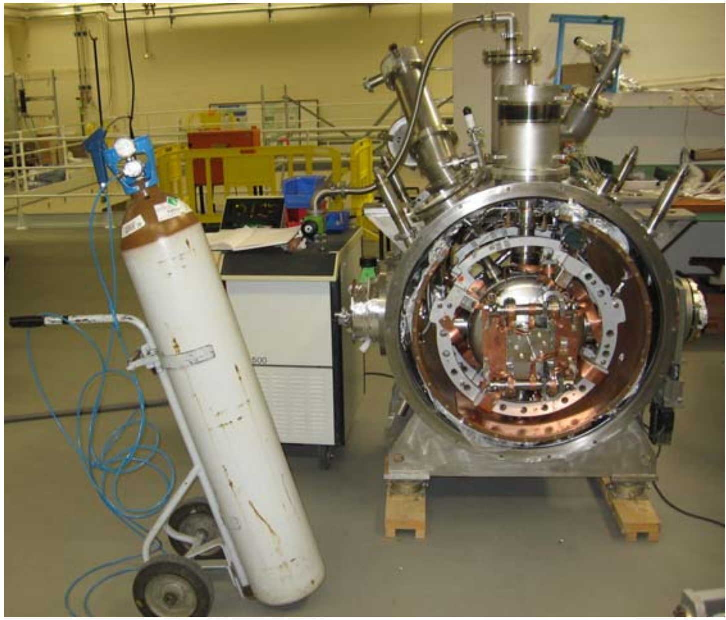
- Single spoke prototypes (β 0.15, β 0.35) built & successfully tested; β 0.35 reached 12.5 MV/m (βλ definition)

- CW power couplers fabricated and conditioned successfully, using a 10kW solid-state amplifier **E.Rampnoux WE5PFP029**

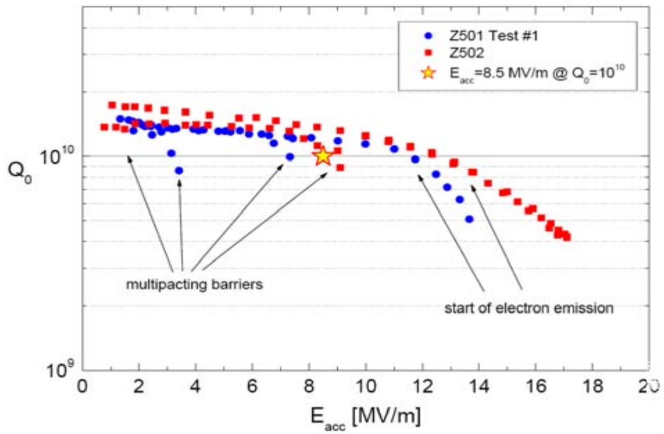
- β 0.15 cavity successfully tested in horizontal cryostat with Cold Tuning System (incl. piezo-actuators) & digital LLRF loop

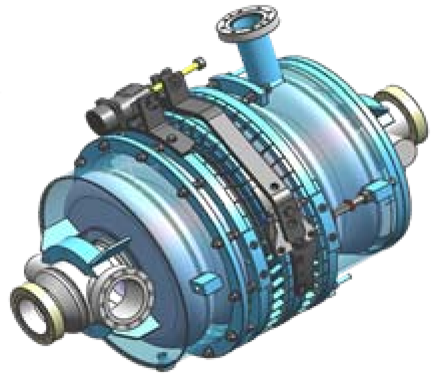
- Fast detuning procedures checked (< 5ms without significant instabilities during the transient)

- NEXT STEP, coming soon = global test @ full power (10kW)



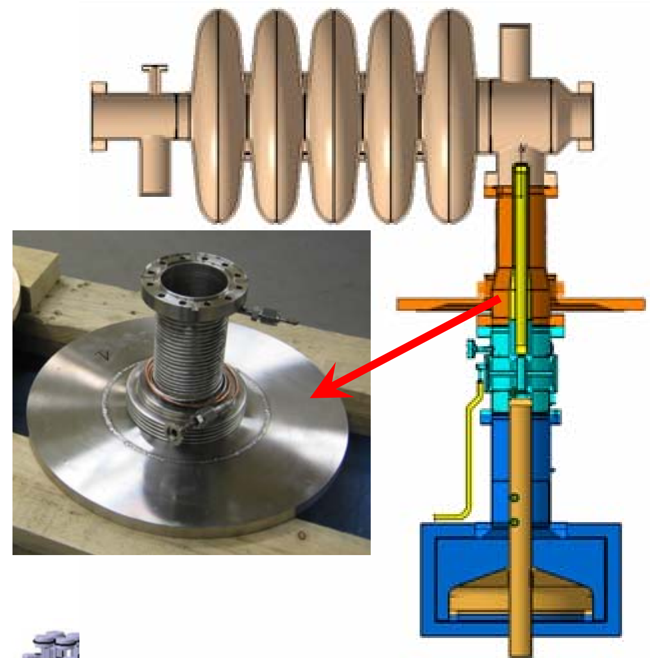
700 MHz module prototyping





INFN

cnrs In2p3



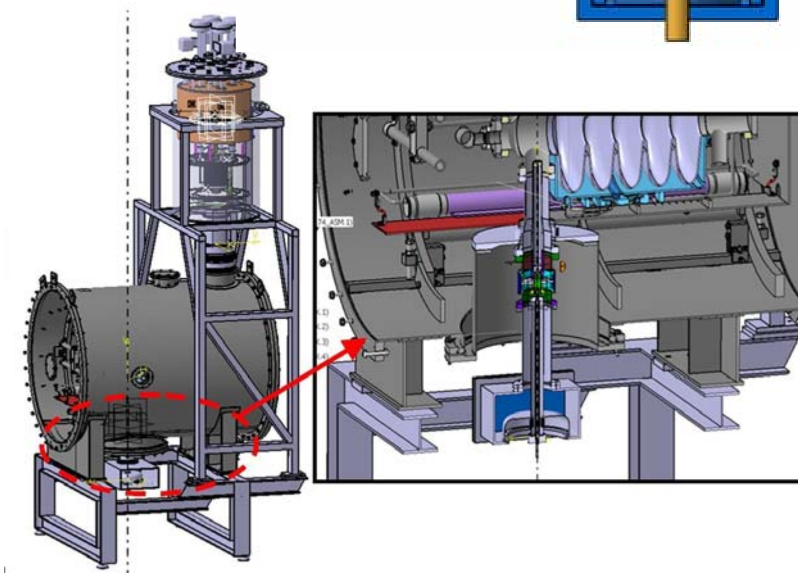
- 5-cell β 0.5 elliptical prototype built & successfully tested

- 150 kW CW power couplers under construction, a 80 kW IOT tube (TED) is available, to be commissioned

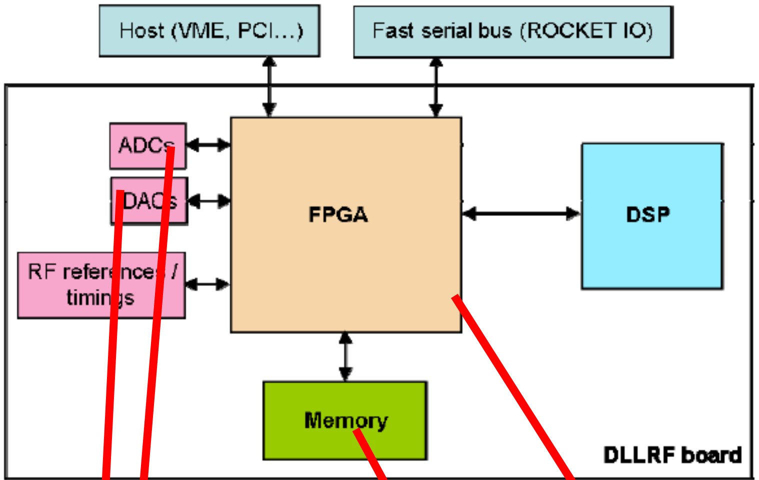
- Prototypical cryomodule designed, presently being built

- **GOAL1** = qualify the reliability performance of a high-energy cryomodule at full power & nominal temperature

- **GOAL2** = in the long run, provide a test bench for fast fault-recovery scenarios



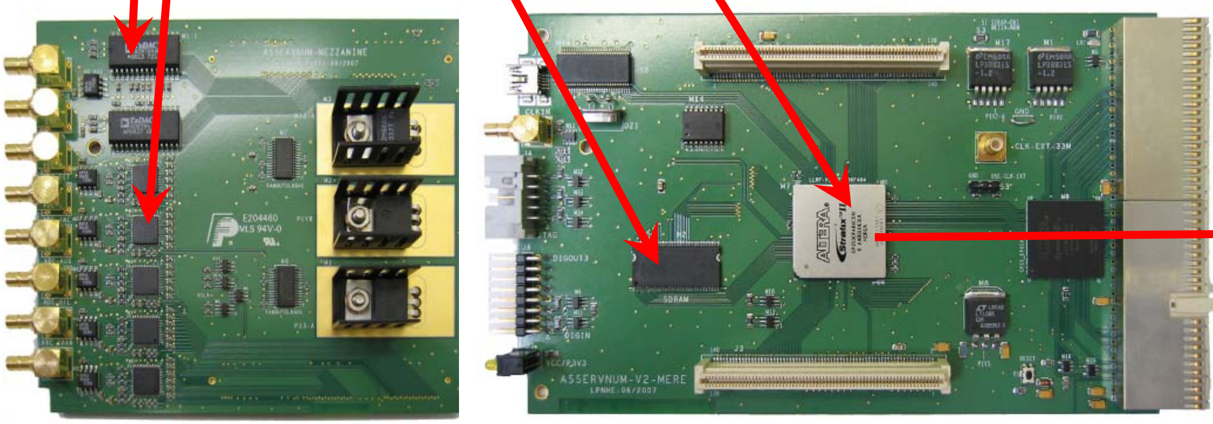
Digital LLRF activities



XT-ADS DLLRF reference scheme (suited to fault-tolerance procedures)

- a FPGA chip, able to process the feedback control algorithms,
- several ADCs and DACs, to convert the received and produced signals,
- a RAM memory, used to store set-points or save operating parameters,
- a serial bus, to communicate with the general control/command system,
- a fast serial bus, to communicate with adjacent boards.

1st IPNO prototype showed very good regulation stability with spoke cavities: <1% (V) & <0.5°(φ) @2σ



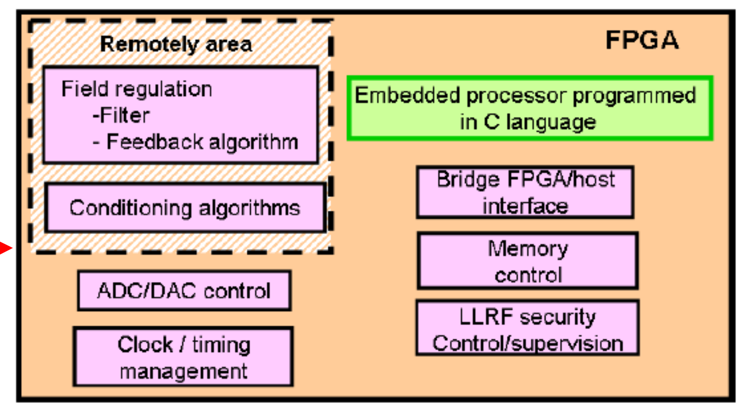
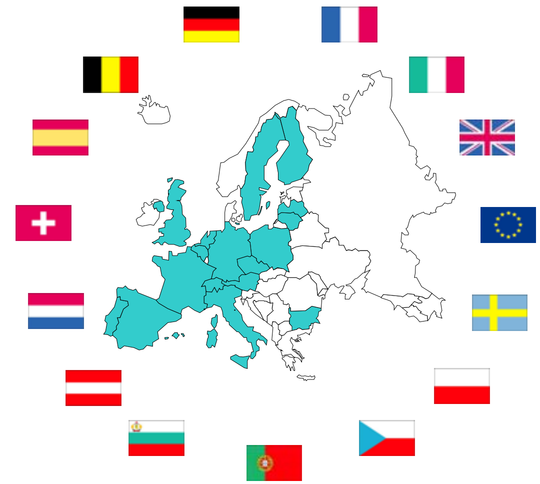


Figure 12: Internal architecture of FPGA

2nd IPNO prototype is presently under validation tests



1. The European ADS demonstrator project
2. The XT-ADS linac reference scheme
3. The reliability issue
4. Related R&D topics

5. Conclusion

Conclusions & Perspectives

IP-EUROTRANS
- INTEGRATED PROJECT ON EUROPEAN TRANSMUTATION -
SIXTH FRAMEWORK PROGRAMME

➲ **A reliability-oriented superconducting linac has been identified as the reference solution for the European ADS Transmutation Demonstration**

THANK YOU

➲ **An advanced design of the machine is in-work, to be frozen by 2010**

for your attention !

➲ **R&D activities will be pursued after the EUROTRANS contract (ends April 2010), especially on the very challenging reliability issue**

★ Beyond this, the MYRRHA machine ?! ★

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- **Conceptual Design Team** being settled @Mol, Belgium (2009-2012, supported by EU FP7)

- Goal n°1: **demonstrate the transmutation**

- Goal n°2: **build a flexible irradiation facility** as suitable replacement for the existing reactor BR2

- Timescale: **fully operational in 2020**